EF02 Summary + Next Steps

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September 3rd, 2021

What is Higgs BSM in the context of Snowmass? A brief reminder…

The big questions:

- Is there something more to EWSB?
- Is there a solution for the naturalness problem?
- Higgs and EW phase transition
- Higgs and Flavor
- Higgs portal

How do we study these at future colliders?
What detectors and computing/electronics do we need to study these phenomena?
What about improvements in Analysis Techniques?

Precision Higgs SM measurements are under EF01 but any deviations from SM measurements fall under EF02

- Collaboration between EF01/EF02

Previous Meetings

Ef02 Indico Page

November 2020

12 Nov EF02: LOI Review Part 2!!

October 2020

01 Oct EF02: LOI Review!

September 2020

03 Sep Higgs and Flavor

August 2020

07 Aug Higgs and Flavor

June 2020

26 Jun EF02: Triple Higgs Coupling, Quartic, Quintic + more Higgs Friends

12 Jun EF02: 2HDM Meeting

May 2020

15 May EF02 Kickoff Meeting

+ meetings in collaboration with EF01

Previous Meetings

+ LOI reviews!

Previous Meetings

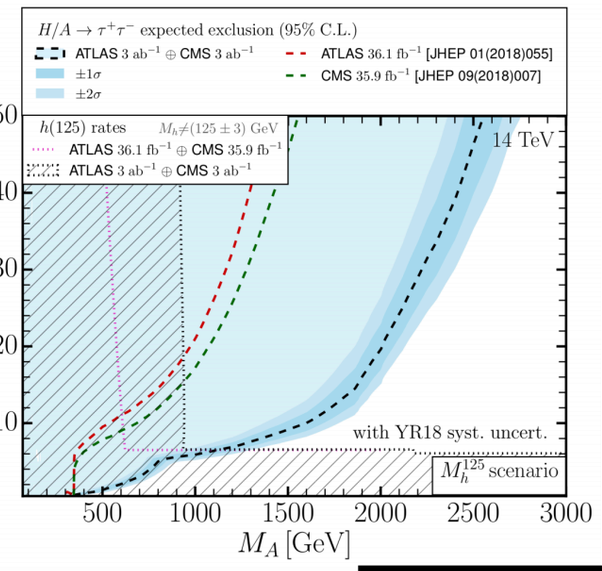
Indirect: Measure h(125)

$y_{\mathrm{2HDM}}/y_{\mathrm{SM}}$	2HDM 1	2HDM 2
hVV	$1-\delta^2/2$	$1-\delta^2/2$
hQu	$1-\delta/t_\beta$	$1-\delta/t_\beta$
hQd	$1-\delta/t_\beta$	$1+\delta t_\beta$
hLe	$1-\delta/t_\beta$	$1+\delta t_\beta$
HVV	$-\delta$	$-\delta$
HQu	$-\delta-1/t_\beta$	$-\delta-1/t_\beta$
HQd	$-\delta-1/t_\beta$	$-\delta+t_\beta$
HLe	$-\delta-1/t_\beta$	$-\delta+t_\beta$
AVV	0	0
AQu	$1/t_\beta$	$1/t_\beta$
AQd	$-1/t_\beta$	t_β
ALe	$-1/t_\beta$	t_β

[N. Craig]

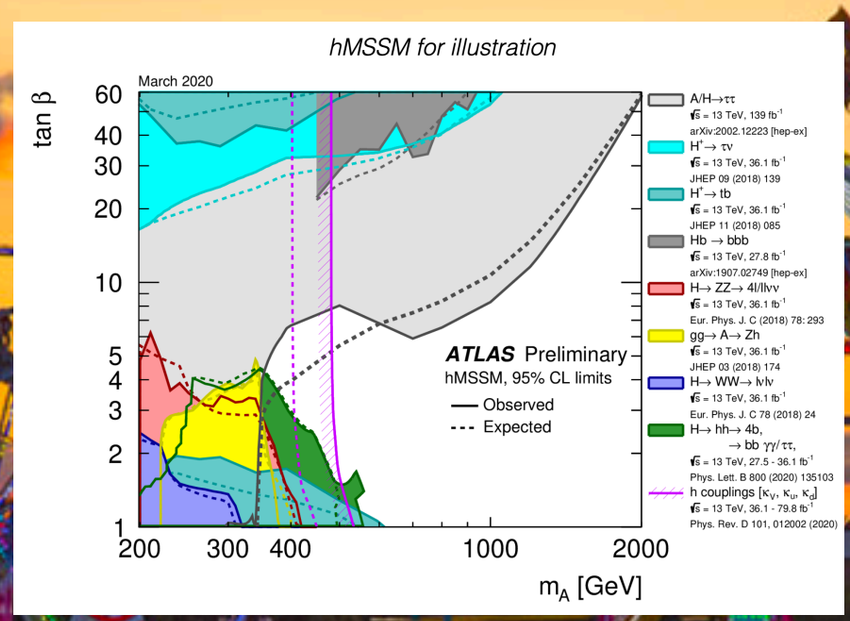
Direct: Search for H/A/H±

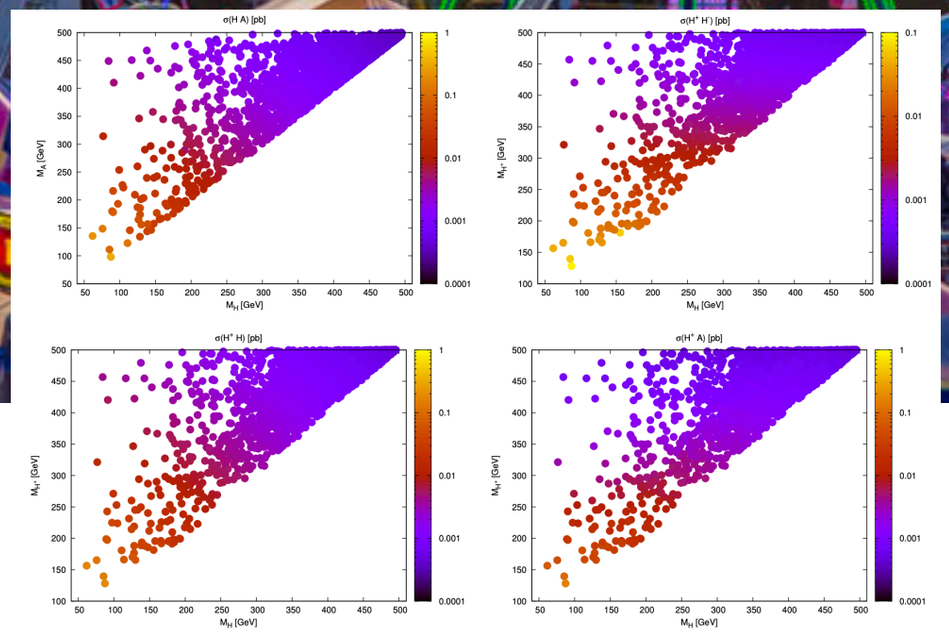
2HDM



[P. Roloff]

Higgs and Flavor Part 1, Part 2





[T. Robens]

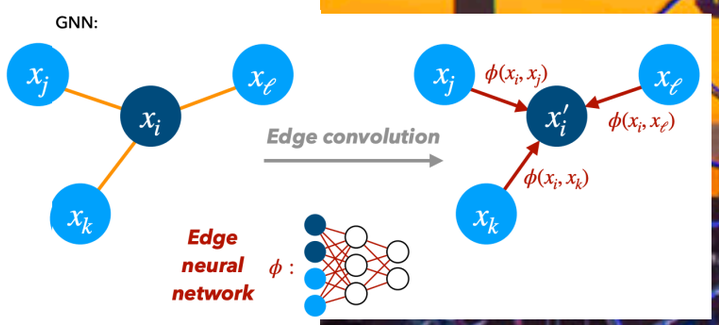
Triple Higgs Coupling, Quartic, Quintic + more Higgs Friends

+ LOI reviews!

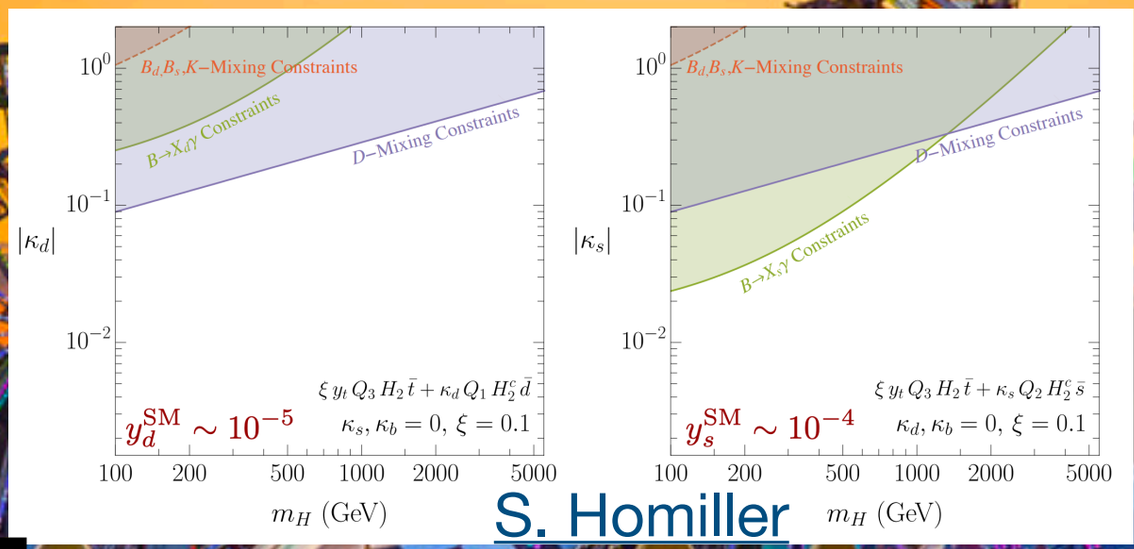
Previous Meetings

Triple Higgs Coupling, Quartic, Quintic + more Higgs Friends

2HDM

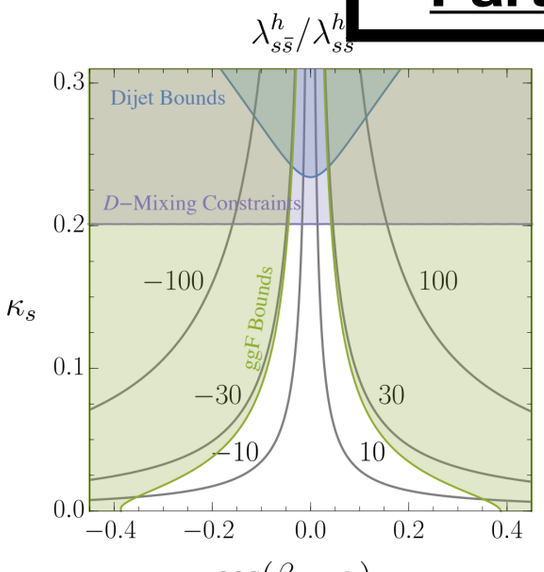


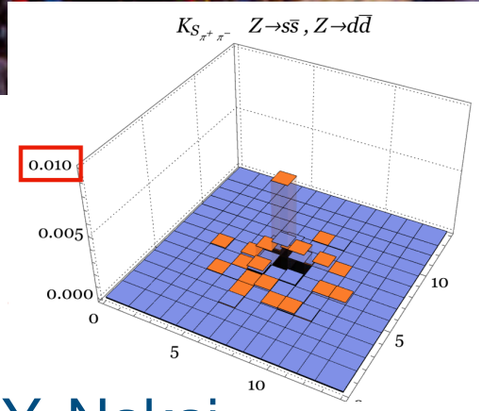
J. Duarte



S. Homiller

Higgs and Flavor Part 1, Part 2





← **4th color !**

$Z \to s\bar{s}$ $(p_T > 20$ GeV$)$

$Z \to d\bar{d}$ $(p_T > 20$ GeV$)$

Y. Nakai

+ LOI reviews!

Previous Meetings

2HDM

Higgs and Flavor
Part 1, Part 2

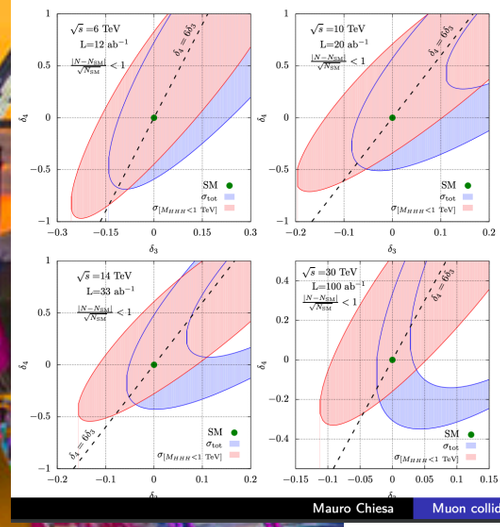
C. Vernieri

	collider	single-H	HH	combined
	HL-LHC	100-200%	50%	50%
	$CEPC_{240}$	49%	–	49%
	ILC_{250}	49%	–	49%
	ILC_{500}	38%	27%	22%
	ILC_{1000}	36%	10%	10%
	$CLIC_{380}$	50%	–	50%
	$CLIC_{1500}$	49%	36%	29%
	$CLIC_{3000}$	49%	9%	9%
	FCC-ee	33%	–	33%
	FCC-ee (4 IPs)	24%	–	24%
	HE-LHC	-	15%	15%
	FCC-hh	-	5%	5%

These values are combined with an independent determination of the self-coupling with uncertainty 50% from the HL-LHC.

Triple Higgs Coupling, Quartic, Quintic + more Higgs Friends

Sensitivity to δ_3 and δ_4 (small δ_3)



- no cuts
- $M_{HHH} < 1$ TeV

$\delta_3 = 0$

6 TeV $\delta_4 \sim [-0.45, 0.8]$

10 TeV $\delta_4 \sim [-0.4, 0.7]$

14 TeV $\delta_4 \sim [-0.35, 0.6]$

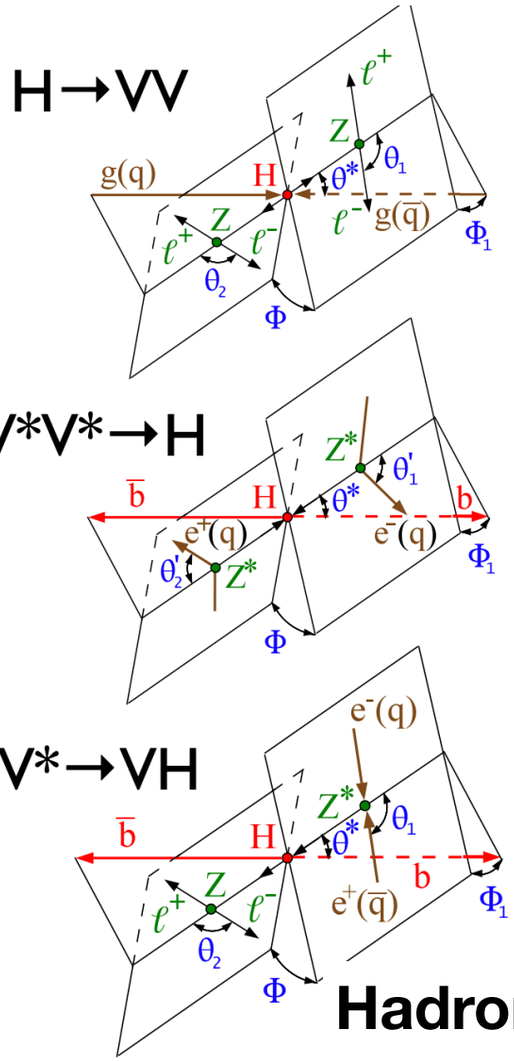
30 TeV $\delta_4 \sim [-0.2, 0.5]$

Mauro Chiesa | Muon collider: quartic Higgs coupling

M. Chiesa

+ LOI reviews!

This past week:
Status of Higgs CP Studies



- Higgs Physics at the HL-LHC and HE-LHC

  WG2 report: arXiv:1902.00134

A. Gritsan

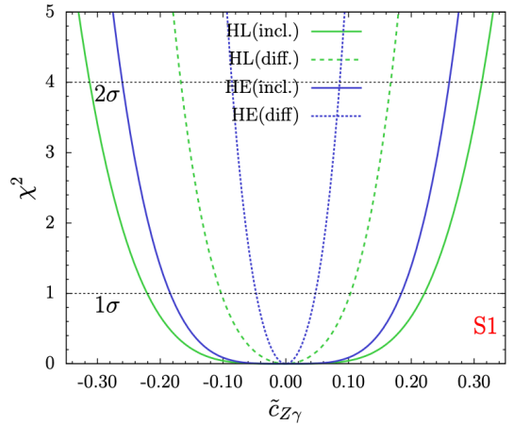
— Global fits also target CP-odd couplings

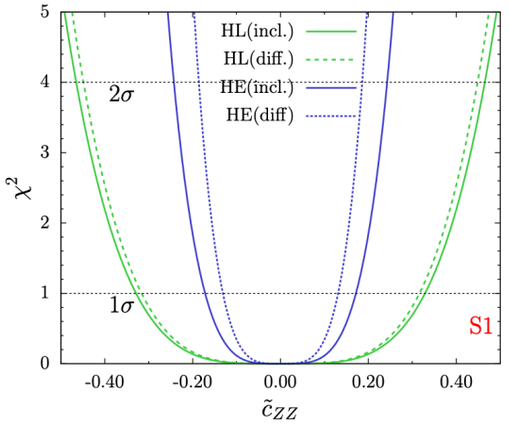
$$\chi^2(\tilde{c}_{Z\gamma}, \tilde{c}_{ZZ}) = \sum_{i,f} \frac{(\mu_{i,f} - \mu_{i,f}^{\text{obs.}})^2}{\Delta_{i,f}^2}$$

— be careful to interpret yield as CP…

CP-even CP-odd

$$\mu_{ZH}^{14\text{TeV}} = 1.00 + 0.54\,\tilde{c}_{Z\gamma}^2 + 2.80\,\tilde{c}_{ZZ}^2 + 0.95\,\tilde{c}_{Z\gamma}\tilde{c}_{ZZ}$$
$$\mu_{WH}^{14\text{TeV}} = 1.00 + 0.84\,\tilde{c}_{Z\gamma}^2 + 3.87\,\tilde{c}_{ZZ}^2 + 3.63\,\tilde{c}_{Z\gamma}\tilde{c}_{ZZ}$$
$$\mu_{\text{VBF}}^{14\text{TeV}} = 1.00 + 0.25\,\tilde{c}_{Z\gamma}^2 + 0.45\,\tilde{c}_{ZZ}^2 + 0.45\,\tilde{c}_{Z\gamma}\tilde{c}_{ZZ}$$





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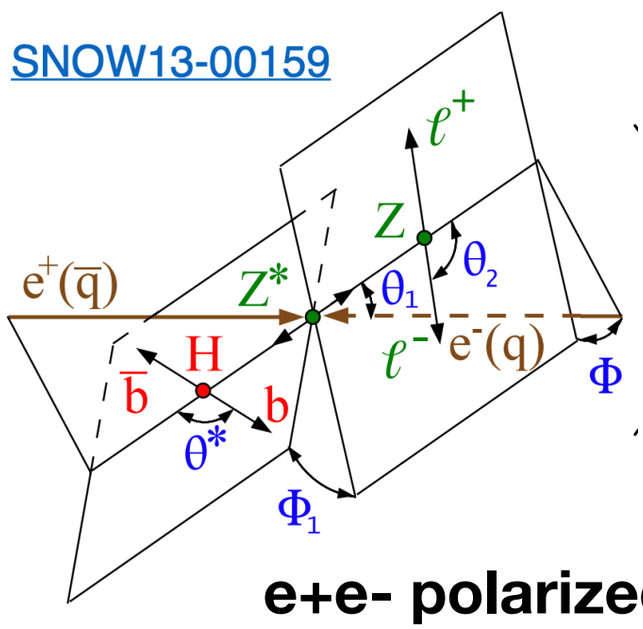


Photon collider is unique with focus on $H\gamma\gamma$ coupling

— photon beam polarization is critical for CP

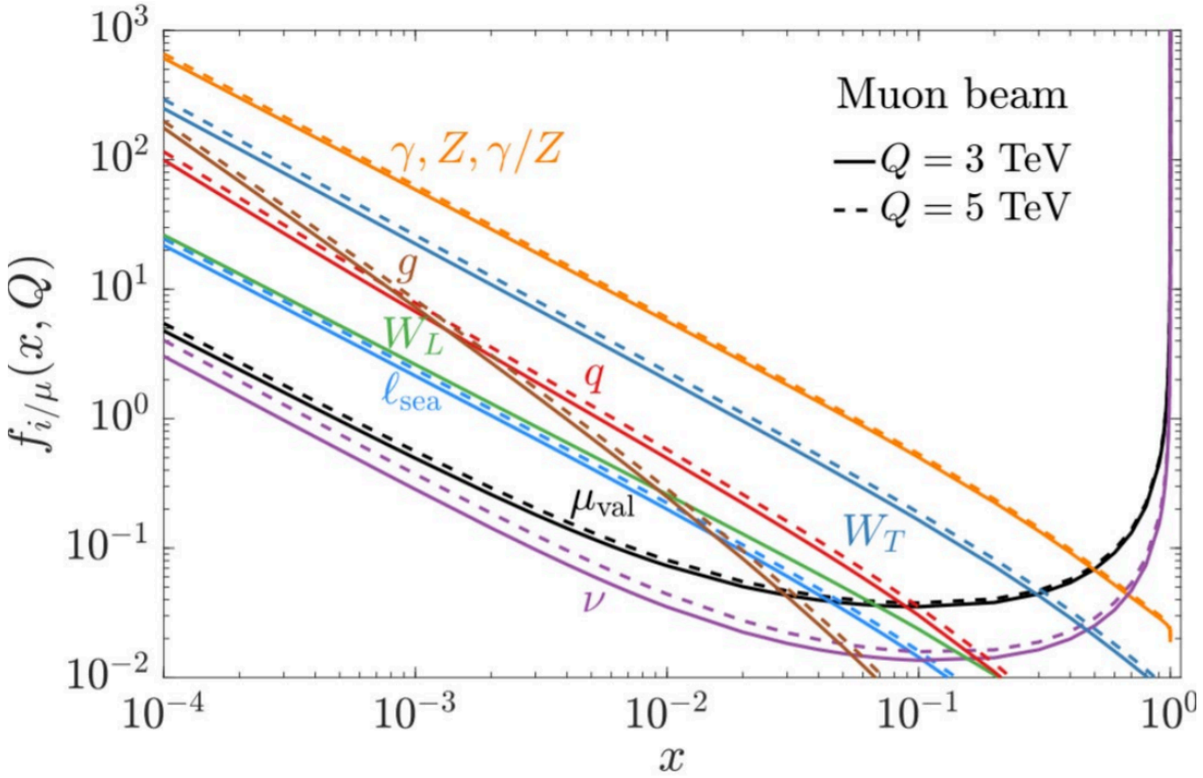
— most interesting parameter:

$$\mathcal{A}_3 = \frac{|A_\parallel|^2 - |A_\perp|^2}{|A_\parallel|^2 + |A_\perp|^2} = \frac{2\mathcal{R}e\,(A^*_{--}A_{++})}{|A_{++}|^2 + |A_{--}|^2} = \frac{|a_2|^2 - |a_3|^2}{|a_2|^2 + |a_3|^2} = (1 - 2f_{CP})$$

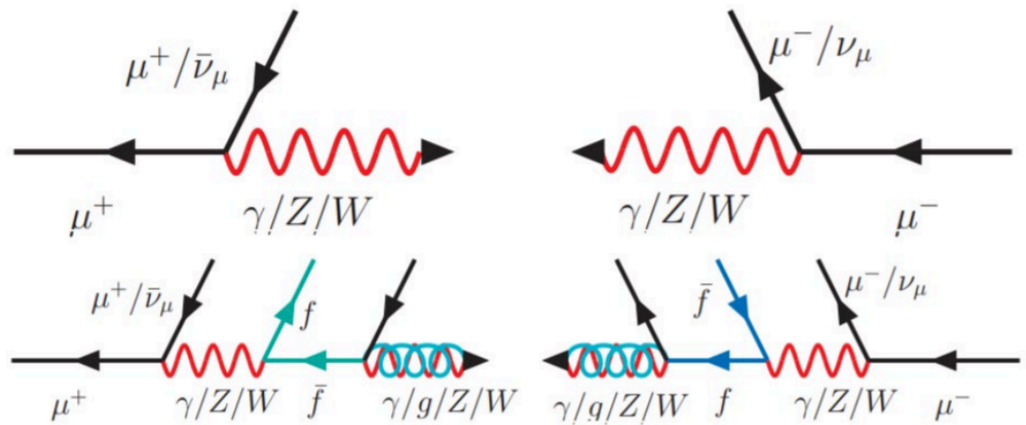
Detecting and Studying Higgs Bosons at a Photon-Photon Collider: arXiv:hep-ph/0110320

This past week:
Update on Higgs Studies at a Muon Collider

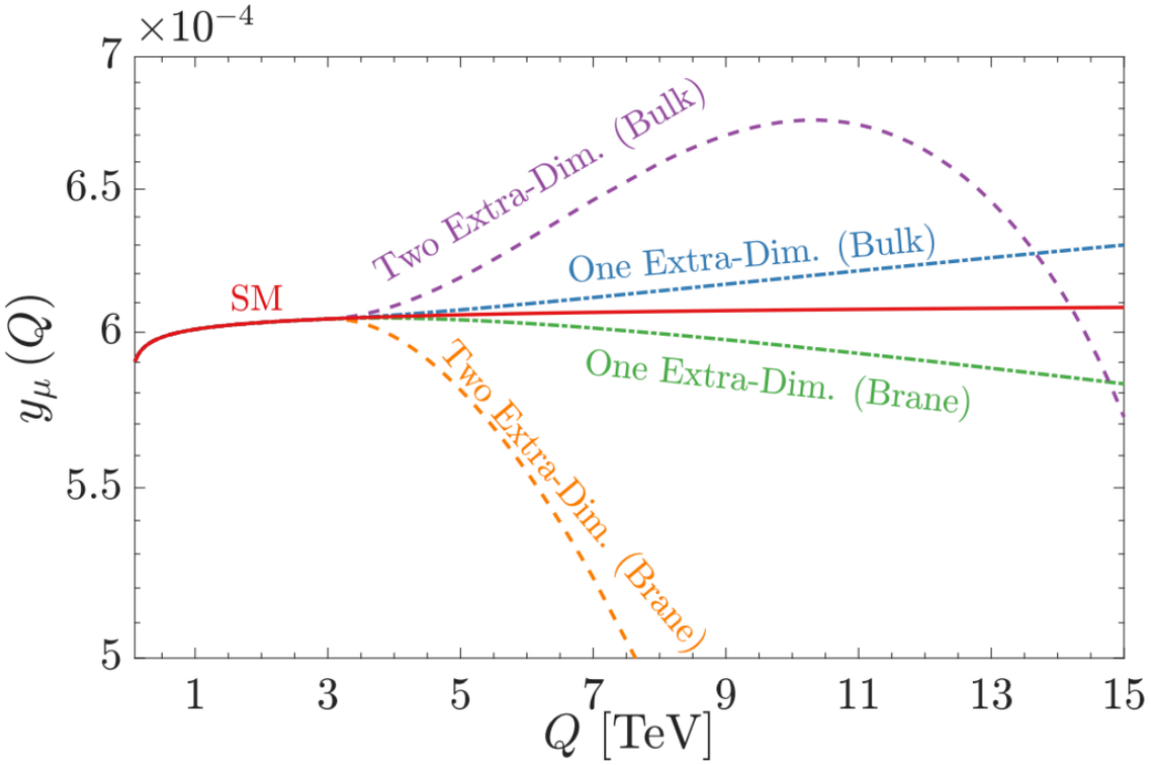
Z. Liu



High Energy Muon Collider provides a vibrant and growing Higgs physics program



Muon Structure



Higgs Precision

	Fit Result [%]		
	10 TeV Muon Collider	with HL-LHC	with HL-LHC + 250 GeV e^+e^-
κ_W	0.06	0.06	0.06
κ_Z	0.23	0.22	0.10
κ_g	0.15	0.15	0.15
κ_γ	0.64	0.57	0.57
$\kappa_{Z\gamma}$	1.0	1.0	0.97
κ_c	0.89	0.89	0.79
κ_t	6.0	2.8	2.8
κ_b	0.16	0.16	0.15
κ_μ	2.0	1.8	1.8
κ_τ	0.31	0.30	0.27

Future Meetings

Wednesdays 12-2pm

September 8th 2021 - Updates from working groups
September 29th 2021 - Global Fits, Complementarity
November 10th 2021 - Higgs + Dark Matter

More ideas welcome!

Meetings once every three weeks, trade off with EF01, EF02 and EF10

Conclusions

Encourage the US community to coalesce around a single longterm sustainable plan to study the Higgs and BSM

Considerations:

- ***Interesting physics reach!*** (Measurements + Searches + Complementarity across frontiers)
- **Timeline** - Initial program can come online within 10-20 years, future programs build on initial lessons learned
- **Program Sustainability** - Technology which will be useful across collider/detector designs and across frontiers
- **Broader Impacts** - (combination of all the above) and impact on the US community

Backup

Conclusions

- we studied the sensitivity of the muon collider to the Higgs quartic coupling by considering the process $\mu^+\mu^- \to HHH\nu\bar{\nu}$
- no background was considered
- (almost) no optimization based on kinematics was performed
- the sensitivity increases with $\sqrt{s}$ and/or the luminosity

$\sqrt{s}$ [TeV]	L [ab^{-1}]	δ_4 (arbitrary δ_3)	δ_4 ($\delta_3 = 0$)
6	12	[-1,1.7]	[-0.45,0.8]
10	20	[-0.7,1.55]	[-0.4,0.7]
14	33	[-0.55,1.4]	[-0.35,0.6]
30	100	[-0.35,1.2]	[-0.2,0.5]

- under (reasonable) assumptions on the energy and the luminosity, the muon collider can do a pretty good job in constraining the quartic Higgs coupling